A New Microwave Synthesis Chain for the Primary Frequency Standard NIST-F1

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***Abstract*—We present the design and measurements of the microwave synthesis chain presently used in NIST-F1, the laser-cooled cesium fountain primary frequency standard in operation at NIST, Boulder, CO. The chain has been used in two accuracy evaluations of NIST-F1 (January 2005 and July 2005), each of which had a combined (Type A and Type B) fractional frequency uncertainty of ~ 0.5×10^{-15}. Additionally, this synthesis chain was in use during a recent calibration of the $^{199}Hg^{+}$ optical clock transition against Cs, which had a fractional uncertainty of 9.1×10^{-16}.**

I. Introduction

NIST-F1 is a laser-cooled cesium (Cs) fountain primary frequency standard in operation at NIST, Boulder, CO [1, 2]. An evaluation of the accuracy of NIST-F1 ultimately calibrates the frequency of a hydrogen maser in the NIST clock ensemble with respect to the SI second, defined as the unperturbed ground state hyperfine splitting in Cs, 9 192 631 770 Hz. A microwave synthesis chain uses 5 MHz and 100 MHz reference signals from the hydrogen maser to generate the 9.193 GHz signal used to interrogate the Cs clock transition. It is important that the synthesis chain not only produces high-quality microwaves, which support the short-term stability of NIST-F1 (set by the number of detected atoms), but also does not introduce any noise that can bias the frequency. Here the term synthesis chain describes the entire link from the hydrogen maser to the Cs atoms within the NIST-F1 physics package. The term synthesizer describes only the unit that generates 9.193 GHz from a reference frequency (100 MHz).

II. Synthesis Chain

A. Overview

A simplified schematic of the NIST-F1 synthesis chain is shown in Fig. 1. Not shown for simplicity is the synthesizer used to generate the 9.193 GHz used for atomic state-selection. The important elements are the hydrogen maser, the high-quality (BVA) quartz oscillator, the synthesizer, and the time-difference measurement unit. The maser generates reference signals at 5 MHz and 100 MHz, which are delivered to the NIST-F1 laboratory by use of high-quality RF cables. An exceptionally stable BVA type quartz oscillator is locked to the maser with a time constant of $\tau \approx 10$ s, and a 100 MHz reference from this PLL (phased-locked loop) circuit is fed to the synthesizer module. This scheme is designed to realize the short-term stability offered by the atom number of NIST-F1 while maintaining reference to the maser in the long-term. So, at short times ($\tau < 10$ s) the fountain stability is supported by the excellent stability of the BVA quartz. At longer times, ($\tau > 10$ s) the quartz is locked to the maser, which has better stability in the long-term. Placing the multiplication chain within the PLL as shown suppresses noise due to temperature coefficients by a factor of ~20 compared to multiplying outside the loop.

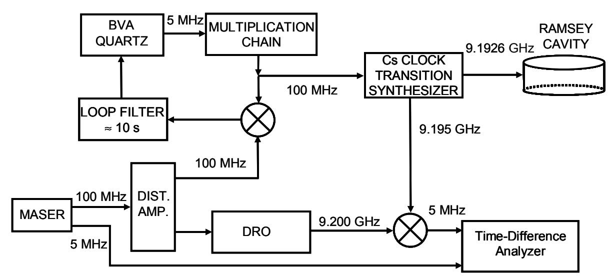

Figure 1. A simplified schematic of the NIST-F1 microwave synthesis chain.

The other components of the synthesis chain are part of a very sensitive monitoring system. A second DRO generates microwaves at 9.200 GHz, which are compared to a 9.195 GHz reference output of the 9.1926 GHz synthesizer (this is phase coherent with the 9.193 GHz sent to the NIST-F1 cavity) producing a 5 MHz beat frequency. This 5 MHz is compared to the 5 MHz reference from the maser by use of a commercial time-difference measurement system. This unit measures the phase difference between the two signals, and the results are recorded once a second by the computer that operates NIST-F1. Discontinuities in the recorded phase

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14. ABSTRACT
We present the design and measurements of the microwave synthesis chain presently used in NIST-F1, the laser-cooled cesium fountain primary frequency standard in operation at NIST, Boulder, CO. The chain has been used in two accuracy evaluations of NIST-F1 (January 2005 and July 2005), each of which had a combined (Type A and Type B) fractional frequency uncertainty of ~ 0.5 ?10-15. Additionally, this synthesis chain was in use during a recent calibration of the 199Hg+ optical clock transition against Cs, which had a fractional uncertainty of 9.1 ?10-16.

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difference indicate possible problems in the microwave chain and the corresponding fountain data are flagged as potentially corrupt. This monitoring system was included in the design because the previous synthesizer contained insufficiently sensitive monitoring electronics. Specifically, LEDs on the front panel indicated when PLL correction voltages reached tuning limits. However, we discovered that the fountain measurements had often been corrupted many days earlier. This resulted in several instances of rejecting large quantities (many days) of fountain data.

B. The Synthesizer

The microwave synthesizer previously used in NIST-F1 was based on an architecture developed for use on NIST-7 [3], the last thermal beam primary standard used at NIST. The complexity and age (over 10 years) of this unit had made maintenance and repair difficult. Since superior technology is presently commercially available, we replaced this synthesizer with a unit based on DROs (dielectric resonant oscillators), similar in design to that described in [4]. A schematic diagram of the synthesizer architecture is shown in Fig. 2.

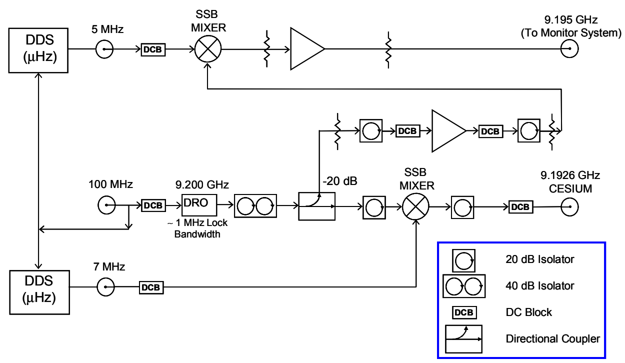

Figure 2. A schematic of the 9.193 GHz NIST-F1 synthesizer.

A 100 MHz reference signal is fed to a DRO producing a signal at 9.200 GHz. This signal is then split to two separate paths. In the lower path, shown in Fig. 2, the 9.200 GHz and 7.368 MHz from a computer controlled DDS (Direct Digital Synthesis) with μHz resolution are sent into a SSB (Single-Sideband) mixer to produce microwaves at the Cs clock transition frequency, 9.1926 GHz. The other half of the 9.200 GHz from the DRO is part of the monitoring system and the signal path is shown in the upper portion of Fig. 2. Here, the 9.200 GHz is combined with 5 MHz in a second SSB mixer generating 9.195 GHz. This signal is mixed with 9.200 GHz signal originating from a second DRO also referenced to a 100 MHz signal as shown in the synthesis chain (Fig. 1). The resulting 5 MHz beat note is compared against the 5 MHz maser reference with a commercial time difference analyzer. This commercial unit measures the phase difference between these two signals and logs the result into its internal memory or to an external computer once per second. Fig. 3 shows a photograph of the components inside the synthesizer module. Note that all the components are commercially available and this leads to an uncluttered and easily accessible architecture.

III. MEASUREMENTS

The microwave synthesis chain has undergone a variety of tests and has been used in two formal accuracy evaluations of NIST-F1 (January and July 2005), each of which had a combined (Type A and Type B) fractional frequency uncertainty of ~ 0.5×10^{-15}. Also, the system was used during measurements of the absolute frequency of the $^{199}Hg^+$ single-ion optical clock at NIST Boulder, which had a fractional uncertainty of 9.1×10^{-16} [5]. Presented here are measurements of the phase noise of the system and long-term measurements of the stability.

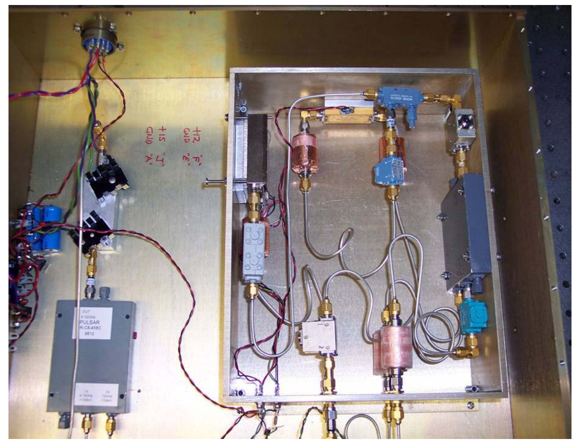

Figure 3. A photograph of the interior of the Cs microwave synthesizer.

A. Phase Noise Measurements

The setup shown in Fig. 4 was used to measure the phase noise of the synthesizer out to 10 kHz. The results of this measurement are shown in Fig. 5. For comparison, the phase noise of a synthesizer based on a high-quality BVA type quartz oscillator is also presented. This curve was obtained by taking the measured phase noise of a BVA type quartz oscillator and scaling the performance up to 9 GHz. This measurement shows the phase noise of the frequency

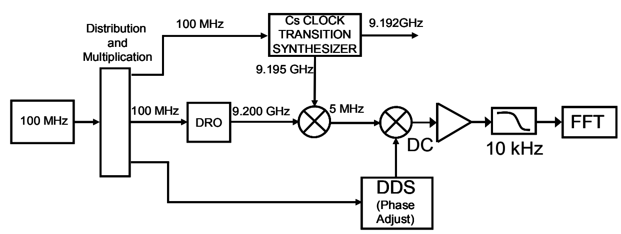

Figure 4. A schematic diagram of the setup used to measure the residual phase noise of the synthesizer used to interrogate the 9.193 GHz Cs clock transition.

synthesis is typically 10 to 20 dB lower than the BVA performance when multiplied to 9.2 GHz. The synthesizer is not a significant source of noise in the experiment. The observed spurs in the spectrum are small and are not expected to be the source of bias.

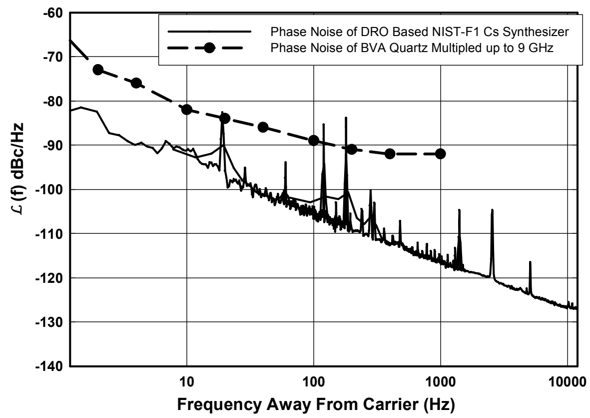

Figure 5. Measured residual phase noise of the DRO based synthesizer.

B. Stability Measurements

The long-term stability of the main synthesizer against the monitor synthesizer and of the entire chain, as shown in Fig. 1 was measured with the commercial time-difference analyzer discussed earlier. The comparison of the 9.193 GHz synthesizer against the monitor synthesizer, shown in Fig. 6, was made with both units operating from a common reference source.

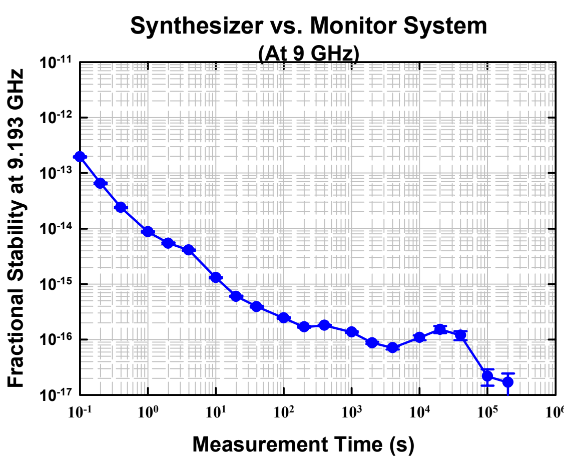

Figure 6. The long-term stability of the Cs synthesizer against the monitor synthesizer.

The instability of the DRO based synthesizers (common reference) is much less than that of the fountain at all measured times and shows that they are not a significant source of noise in NIST-F1. The measurement of the stability of the entire chain, shown in Fig. 7, is compared to the stability of NIST-F1 operating in a high density mode, $\sigma_y(\tau) \approx 2 \times 10^{-13}\tau^{-1/2}$. This illustrates that the chain is unbiased relative to the fountain stability at all measurement times.

The stability plot in Fig. 7 shows added instability at ~2×10^4 s, but continues to drop at times beyond this. We are reasonably confident that this structure is due to poor environmental control in the laboratory in which the measurements were made. This explanation is supported by the plot shown in Fig. 8, which is an estimated stability obtained by taking the Allan deviation of the temperature in the laboratory and assuming that a component in the synthesis chain has a temperature coefficient of 10 ps/K.

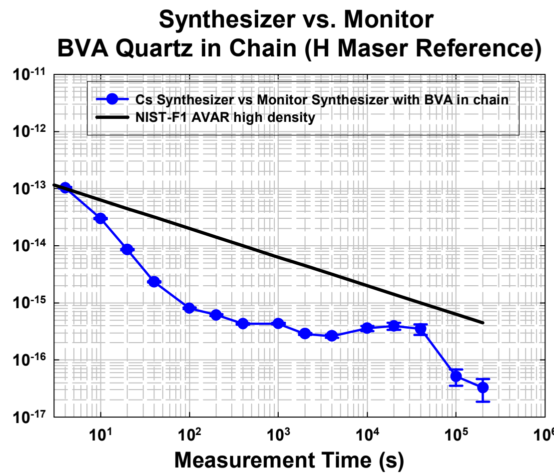

Figure 7. The long term stability of the synthesis chain, as shown in Fig.1, compared to a stability of $2 \times 10^{-13}\tau^{-1/2}$, representing NIST-F1 operating in high density mode.

Additional structure in the stability plot in Fig. 6 between 1 s and 10 s is due the PLL which locks the quartz to the maser. This illustrates how the short-term stability of the synthesis chain operated using only a maser as a reference would be insufficient to support the short-term stability of NIST-F1.

IV. SUMMARY

The synthesis chain and 9.193 GHz microwave synthesizer discussed here are a significant improvement over the previous system employed in NIST-F1. The use of a composite BVA type quartz and maser reference allows for the realization of atom number defined short-term stability while providing the long-term stability of a maser. The DRO synthesizer architecture shows superior phase noise and uses fewer components which are readily available from commercial vendors.

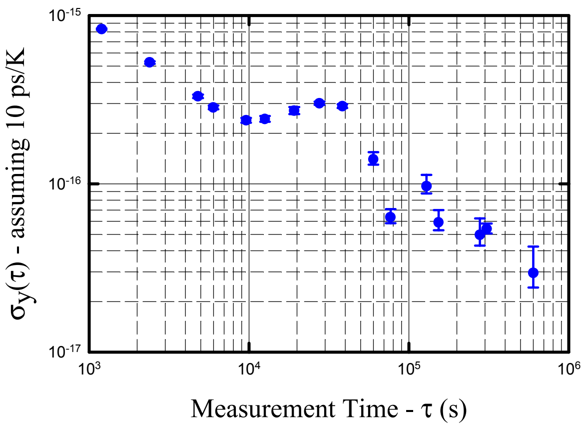

Figure 8. The Allan deviation of the temperature in the NIST-F1 laboratory converted into fraction frequency stability assuming a 10 ps/K temperature coefficient in the synthesis chain.

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REFERENCES

[1] S.R. Jefferts, J.H. Shirley, T.E. Parker, T.P. Heavner, D.M. Meekhof, C.W. Nelson, F. Levi, G. Costanzo, A. DeMarchi, R.E. Drullinger, L. Hollberg, W.D. Lee, and F.L. Walls, "Accuracy Evaluation of NIST-F1," Metrologia, vol. 39, pp. 321–336, Jan. 2002.

[2] T.P. Heavner, S.R. Jefferts, E.A. Donley, J.H. Shirley, and T.E. Parker, "NIST-F1:Recent Improvements and Accuracy Evaluations," Metrologia, vol. 42, pp. 411-422, Sept. 2005.

[3] J.F. Garcia Nava, F.L. Walls, J.H. Shirley, W.D. Lee, and M.C. Delgado Aramburo, "Environmental Effects in Frequency Synthesizers for Passive Frequency Standards," Proc. 1996 IEEE Intl. Freq. Cont. Symp., pp. 973-979, June 1996.

[4] C.R. Ekstrom, E.A. Burt, and T.B. Swanson, "Characterization of the USNO Fountain," Proc. 2001 IEEE Intl. Freq. Cont. Symp., pp. 53-56, June 2001.

[5] W. Oskay, M.J. Jensen, S.R. Jefferts, E.A. Donley, T.P. Heavner, T.E. Parker, K. Kim, T. Fortier, A. Bartels, S.A. Diddams, L. Holberg, W.M. Itano, and J.C. Bergquist, "A Measurement of the Absolute Frequency of the $^{199}Hg^{+}$ Single-Ion Optical Clock,", Submitted.